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A new double-sided grating coupled optical sensor using a cross-shaped microchannel for minimizing the dispersion effect

An-Shik Yang [a], Hsun-Yuan Li [b], Wen-Hsin Hsieh [b],*, Chin-Ting Kuo [a], Yung-Chun Yang [c]

[a] *Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 106, Taiwan, ROC*
[b] *Department of Mechanical Engineering, National Chung Cheng University, Chiayi 621, Taiwan, ROC*
[c] *School of Dentistry, National Defense Medical Center, Taipei 114, Taiwan, ROC*

HIGHLIGHTS

- A new DSGW coupled optical sensor with a cross-shaped microchannel was tested to minimize the dispersion effect.
- The refractive index sensitivity and resolution of sucrose solutions were 26.76 RIU^{-1} and 6.3×10^{-5} RIU.
- The proposed sensor has well demonstrated the immune binding reaction of anti-DNP antibody recognizing DNP.

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ABSTRACT

Optical biosensors have become a powerful detection and analysis tool for broad applications in pharmaceuticals, environmental monitoring and biomedical research. The present paper reports the design, analysis, manufacture and test of a novel double-sided grating waveguide (DSGW) coupled optical sensor utilizing a cross-shaped microchannel to minimize the dispersion outcome. Numerical and experimental studies were conducted to explore the transport and dispersion phenomena in the microchannel of an optical sensor. In view of the experiments using a sucrose solution as the sample fluid, the detected signals from a DSGW coupler were utilized to appraise the sensor performance in terms of sensitivity and refractive index resolution. The developed optical sensor with the design of cross-shaped microchannel was used to the immunoassay of surface binding reaction of antibodies-dinitrophenol (DNP) recognizing antigens-DNP to display the efficacy of decreasing the unfavorable dispersion effect.

1. Introduction

Optical biosensors have become increasingly important as an effective detection and analysis tool for chemical, biological and medical applications [1]. Various design arrangements combining microchannels with electrical and optical elements have been proposed to perform high-precision downscale biochemical sensing assays with enhanced detection sensitivities, reduced analysis time/test sample volume and miniaturization for chemistry, physics, biology, materials science, clinical diagnostics, environmental monitoring and bioengineering [2–5].

Lately, label-free bioassay technologies have attracted much attention with different types of label-free biosensors formed to attain high sensitivity as compared to fluorescence based measurements. For instance, Goral et al. developed a label-free microfluidic resonant waveguide grating (RWG) biosensor system to sense ligand-directed functional selectivity acting on G protein-coupled receptors (GPCRs) [6]. Kumeria et al. also demonstrated a label-free reflectometric interference spectroscopy (RIfS) based microchip biosensor for detecting circulating tumor cells (CTCs) [7]. To provide a viable alternative for rapid screening of toxins in agriculture products and foods, Xu et al. devised a label-free optical biosensor using gold nanorods (GNRs) as a sensing platform for detection of aflatoxin B1 (AFB1) [8]. Zhang et al. fabricated an efficient porous silicon microcavity (PSM) on silicon-on-insulator (SOI) wafer with great sensitivity and fast response for DNA sensing performance [9]. Subsequently, Orgovan et al. reported the capabilities of the designed optical waveguide lightmode spectroscopy (OWLS) to sensitively monitor adhesion and spreading properties of primary monocytes isolated from human blood [10]. Günther et al. utilized integrated optical detection to characterize residence time distribution (RTD) in microreactor [11].

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* Corresponding author at: Department of Mechanical Engineering, National Chung Cheng University, 168, Sec. 1, University Rd., Min-Hsiung Township, Chiayi 621, Taiwan, ROC.

E-mail address: imewhh@ccu.edu.tw (W.-H. Hsieh).

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Nomenclature

C	species concentration
D	diffusion coefficient
p	pressure
u_i	velocity component in the *i* direction
D_h	hydraulic diameter of the microchannel
Re	Reynolds number

Greek symbols

ρ	density
μ	kinetic viscosity
m	the gradient of the relationship between the measured coupling intensity and the refractive index
σ	system output noise
I	the value of the coupling intensity measured for DI water
I_0	the average value of the coupling intensity measured for DI water

The size of portable fully-packaged optical biosensors has been noticeably condensed through integration of chip-compatible sample handling structures [12,13]. There are two major principles to develop different sensing devices: the surface plasmon resonance (SPR) [14] and the grating coupler [15,16] systems. SPR sensors needed for the biosensing applications are yet restrained to laboratories mainly attributable to their complexity (specialized staff is required), weight, power consumption, fabrication costs, and relatively high expenses of equipment and large size of most currently available instruments [17]. Alternatively, the grating coupler sensors employ a grating to stimulate the guided modes of a planar waveguide. The incident plane-polarized laser can be then diffracted from the grating and initiates to propagate through internal reflections in the waveguide [18]. With inherently superior sensitivity, the sensors measure the changes in the refractive index due to the deposition of biomolecules on the waveguide.

Considerable efforts were completed to develop various label-free grating coupler sensors for biological applications. Sarov et al. demonstrated a novel integrated infra-red laser system by using attenuated total internal reflection from a diffraction grating with near infra-red laser source for micro and nano-fluidic investigation and analysis [19,20]. Darwish et al. illustrated a dual-grating coupler biosensor having a four-channel configuration to complete a resolution limit of 10^{-5} refractive index units (RIU) for monitoring the human serum albumin (HAS) recognition event [21]. As an array sensor chip, Wei et al. developed a reflective grating coupler sensor using the electron beam lithography and reactive ion etching (RIE) on a porous silicon waveguide to detect changes in the reflection angle as a result of DNA binding to the grating surface [22]. Adányi et al. formed OWLS based immunosensors to determine vitellogenin (Vtg) in cyprinus carpio with analytical features (limit of detection, specificity and matrix effects) examined [23]. Lin et al. proposed a sensor network based on optical time-division multiplexing (OTDM) to realize the long-period grating (LPG) sensor array [24]. Juknius et al. employed the optical method via excitation of the leaky mode in a sub-wavelength diffraction grating to instantly detect the cell wall changes of gram-positive bacteria *Staphyloccoccus aureus* via different amounts of antimicrobial agent benzylpenicillin [25]. To propose a new technique for the measurements of polyphenol oxidase (PPO), Kim et al. showed an optical waveguide lightmode spectroscopy-based immunosensor by a polyclonal anti-PPO antibody immobilized in situ to the surface of a 3-aminopropyltriethoxysilane-treated optical grating coupler activated with glutaraldehyde [26]. In our prior study [27], an optical sensor having a unique double-sided grating waveguide (DSGW) structure was also presented with the valuable features allowing substantial reduction of the cost and complexity of the experimental setup as well as usage of the sub-surface cavities to adjust the electric field distribution in the grating region for improving the refractive index sensitivity.

In a microchannel flow, hydrodynamic dispersion denotes the normal axial spreading of solute attributable to variations of transverse velocity, leading to radial concentration non-uniformity [28]. Accordingly, the associated radial variations in the concentration distribution can result in the mean concentration over the cross section greater than the concentration at the sensing surface in contact with the reagent. In this case, the concentration difference tends to cause difficulties in conducting the kinetic trials before attaining its steady state, leading to excessive consumption of sample and reagent volumes [29]. Nonetheless, very limited researches were made to improve the microflow process design inside the grating coupled optical sensors for reducing the dispersion intervention in measurements. This study proposed a new DSGW optical sensor with a cross-shaped microchannel to effectively minimize the hydrodynamic dispersion outcome. As a useful tool to investigate the complex dispersal phenomenon, the computational fluid dynamics (CFD) software ANSYS/Fluent® was used to conduct the numerical analysis by solving the transient three-dimensional conservation equations of mass, momentum and species concentration. Both simulations and measurements examined the effects of geometric configuration of the flow channel and Reynolds number on the condition attaining minimization of the dispersion results. To validate the flow and mass transport (including the convection and diffusion) model, the predicted time development of concentration distributions inside the sensor was compared with the visualized fluorescence images. Employing a sucrose solution as the sample fluid, the sensing signals from the waveguide grating biosensor were acquired to explore the sensor performance (in terms of sensitivity and refractive index resolution). We then applied the developed DSGW sensor to the immunoassay of surface binding reaction of antibodies-dinitrophenol (DNP) recognizing antigens-DNP to confirm the effectiveness of reducing the adverse dispersion effect of this microdevice.

2. Device design and fabrication

Fig. 1 illustrates the schematics of optical sensors having (a) the conventional microchannel [27] and (b) the proposed new cross-shaped microchannel. Three modified models of cross-shaped channels were also presented with the major difference in the angles between two inlets. Fig. 2 shows the schematics of optical sensors with the cross-shaped microchannel designs at the angles of (a) 60°, (b) 90° and (c) 120°. The microfluidic channel was made of cyclic olefin copolymer (COC) with the associated design method described below. The cross-sectional dimensions of the flow channel were 3 mm wide and 200 μm high. The extents of the conventional microchannel were 29 mm (L) × 3 mm (W) × 0.2 mm (H), respectively. For the cross-shaped microchannel configuration, the distance from each inlet or outlet port to the junction was